Renewable and Sustainable Energy Reviews 16 (2012) 3344–3354

Contents lists available at SciVerse ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Understanding the temperature-induced mechanical behaviour of energy pile foundations

M.E. Suryatriyastuti [a], H. Mroueh [a,*], S. Burlon [b]

[a] Laboratoire Génie Civil et géo-Environnement Lille Nord de France – Polytech'Lille, Université Lille1 Sciences et Technologies, Villeneuve d'Ascq 59655, France
[b] Institut Français des Sciences et Technologies des Transports, de l'Aménagement, et des Réseaux (IFSTTAR), Paris 75015, France

A R T I C L E I N F O

Article history:
Received 3 February 2011
Received in revised form 18 February 2012
Accepted 20 February 2012
Available online 24 March 2012

Keywords:
Energy piles
Building energy
Heat transfer
Thermal load
Thermo-mechanic behaviour
Condition of contact

A B S T R A C T

This paper discusses physical process of thermal transfer in energy pile foundations, which function as structural support for the buildings as well as heat exchangers serving energy to the buildings. Derivation of conservation of energy balance is presented, depends on its type of heat transfer within a whole system of soil and foundation. In order to understand the mechanical implication behind their application, simulation numeric with finite difference method is conducted, concerning an energy pile in homogenous soil under static thermal load. The study takes into account two different conditions of contact between soil and pile: perfectly contact and sliding contact using frictional interface elements. The results show that temperature-induced mechanical behaviour of pile and soil is strongly related to the condition of contact between them. Further work is projected to consider a more appropriate law that corresponds to cyclic thermal loading of energy piles due to its seasonal cooling and heating operation throughout the year.

Contents

1. Introduction

Utilisation of shallow geothermal energy in providing thermal needs of building is already common. Shallow geothermal energy is the average ground temperature at shallow depth 10–50 m, where its value ranges from 10 °C to 15 °C in most European countries [1]. This kind of technology is well known as conventional ground heat exchanger, where ground thermal energy is extracted from the soil via heat pump connection to the building. The ground operates as heat source supplying warm energy to building during winter season, whilst during summer season it functions as heat sink when cold energy of building is required.

There are two types of conventional ground heat exchangers. The first one is open loop system where the groundwater is used

* Corresponding author.
E-mail addresses: msuryatr@polytech-lille.fr (M.E. Suryatriyastuti), hussein.mroueh@polytech-lille.fr (H. Mroueh), sebastien.burlon@ifsttar.fr (S. Burlon).

1364-0321/$ – see front matter © 2012 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2012.02.062

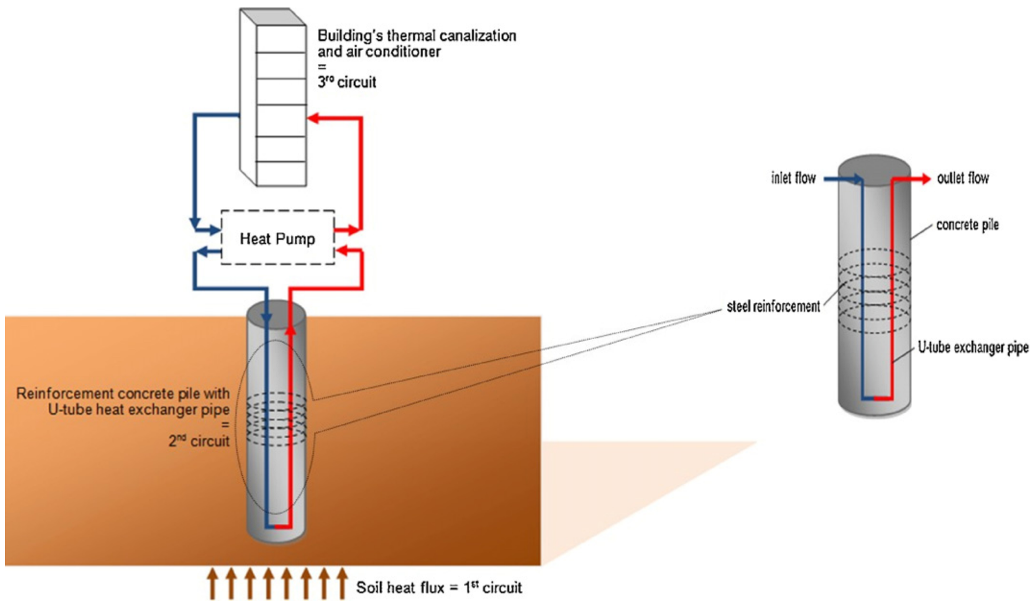


Fig. 1. Energy pile components.

as a heat carrier and pumped directly from an aquifer to the heat pump. The remained waste water is returned to the same aquifer or to another well. This system is simpler but it induces some environment problems like groundwater pollution and needs high cost of maintenance due to clogging in the wells and heat exchangers components.

The second one is closed loop system where closed-coils absorber pipes are embedded into borehole, laid either horizontally or vertically. A heat carrier medium is circulated through absorber pipes to transport heat from the ground to the heat pump. This system is also called as borehole heat exchanger (BHE) system. Because of its high cost of drilling (for vertical loop) and its need of huge land area (for horizontal loop), closed loop system has recently been merged into structural foundation elements.

Energy foundations have both functions as structural elements and heat exchanger elements. This system is like closed-loop conventional ground heat exchanger system unless the absorber pipes are installed on foundation elements. The main advantage of this system is the foundation elements that serve as heat exchangers are already required for structural reason and no need to be constructed separately. Furthermore, concrete as heat transfer medium in energy foundations produces higher thermal energy due to its higher thermal capacity than grout or rock in borehole heat exchanger. Therefore, as well as reduce significantly cost installation and land use, energy foundations are able to increase thermal productivity while preserving environmental sustainability.

Some applications of energy foundations technology have been developed in last decade, such as: Main Tower in Frankfurt-Germany on 1999 (112 energy piles) [2], Keble College in Oxford-UK on 2001 (90 energy piles, 74 MWh annual heating and 55 MWh annual cooling) [3], Dock Midfield Zurich Terminal Airport-Switzerland on 2003 (306 energy piles, 2210 MWh annual heating and 1170 MWh annual cooling) [4], and Lainzer Tunnel Vienna-Austria on 2004 (59 energy piles, 214 MWh annual heating) [1]. All of those projects confirm that utilisation of energy foundation system can save the annual overall costs, even though in the beginning the investment costs are highly expensive. Energy piles application at Zurich Airport reported cost saving up to €36,900 relative to conventional system with annual thermal cost €0.04/kWh [4].

Despite of its successful implementation, there are two main problems of this technology to be considered. One concerns about sustainability of thermal capacity in the system, another concerns about mechanical durability of structure foundation due to thermal solicitation [5]. Derived from those main problems, this paper will discuss separately each problem of particularly energy piles into:

(a) physical process of heat transfer which is influenced by seasonal ground temperature and groundwater flows (Section 3),
(b) thermal transfer balance between soil-concrete foundations-and building (Section 4),
(c) mechanical implication induced by additional thermal loads which change the behaviour of structure (Section 5).

In order to understand energy piles' thermo-mechanical behaviour, preliminary study of an energy pile under static thermal loads in each operation season is being simulated. Since the response of piles to vertical loads strongly depends on the characteristics at the soil–pile interface, it is of major interest to take into consideration the interface condition in the analysis of the behaviour of piles under thermal loading [6,7]. In this study, two comparisons of contact conditions are proposed: perfect contact and sliding contact between soil and pile using frictional interface elements (Section 6).

2. Energy piles system

Energy piles system contains of three principal circuits (Fig. 1). The first circuit is the soil as heat source in winter season where ground energy is withdrawn for heating needs of building. It becomes inversely heat sink in summer season where heat is rejected back to soil in order to recharge ground energy and to cool the building.

The second circuit contains of closed absorber pipes in concrete piles through which heat carrier fluids are circulated to exchange energy from/to soil to/from building. Heat carrier fluids are water with antifreeze solution which is able to avoid freezing at inclination angle of absorber pipes. Hence, glycol–water mixtures are the most suitable solution, containing also additives to prevent corrosion in the header block of valves of the heat pump [8]. Concerning the type of absorber pipes used in energy piles, Hamada et al. [9] conducted performance test of three kinds closed absorber pipes: U-shaped, double U-shaped, and indirect double-pipe in the

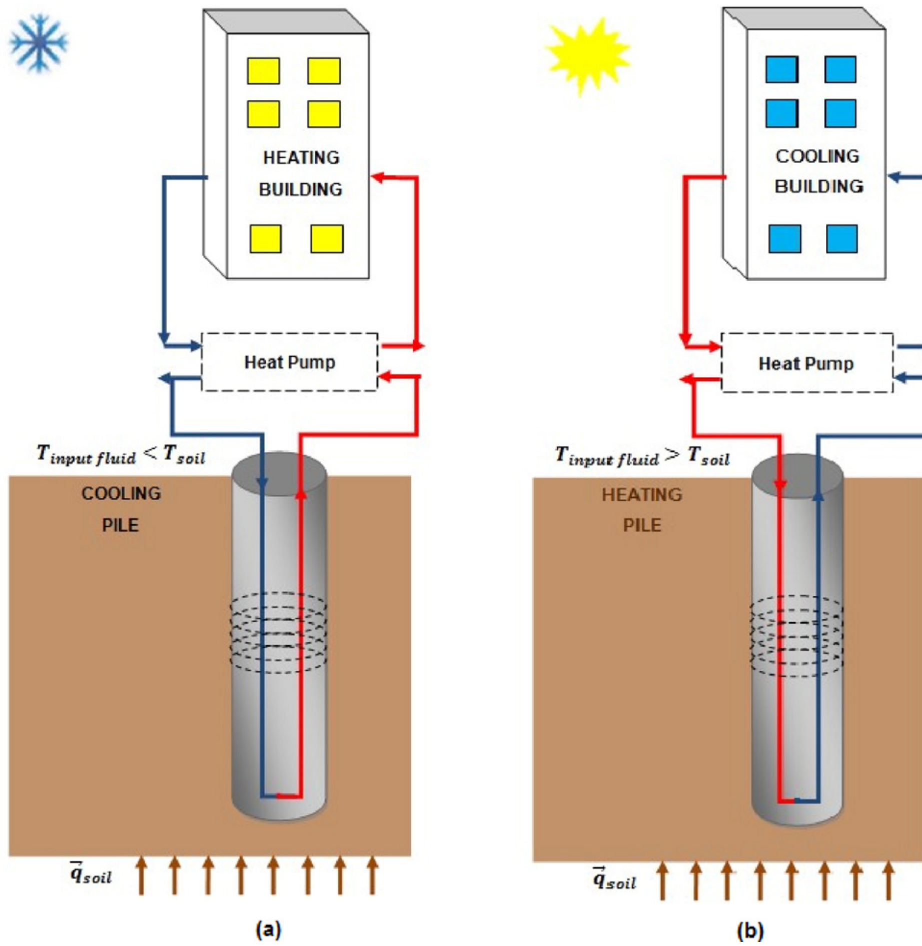


Fig. 2. Scheme of energy piles system operation: (a) energy extraction and (b) energy storage.

building project constructed at Sapporo, Japan. As a result, the U-shaped pipe type was employed from the viewpoint of economic efficiency and workability due to its smallest heat rejection rate [9].

The third circuit is closed-pipelines heating/cooling network which embedded in the floors and walls of building. Heat pumps are linked between second and third circuit in order to raise the original non-usable heat resources to a higher usable room temperature. Quantity of energy production depends on the efficiency of heat pumps, which is described by the coefficient of performance (COP). COP is the ratio of the output energy divided by the input energy (electricity for the compressor) and varies from 3.0 to 6.0 with present equipment (the higher the number the better the efficiency) [10]. For a best energy produced with economical cost, heat pumps require a number of COP higher than 4.0 [8].

Two operation schemes of energy piles are possible: single mode of energy extraction/energy input and seasonal mode operation with heating and cooling storage (Fig. 2). For single mode operation, the energy flow takes place in one direction only, for example: heating purposes in glacial countries or cooling purposes in tropical countries. If only heating or cooling is performed, high permeability ground and high hydraulic gradient of groundwater are of advantage [8]. However, the seasonal operation uses the thermodynamic inertia of the soil in order to store thermal energy in the ground for later operation with reversed energy flow. Consequently, the seasonal operation can produce energy equilibrium automatically in the ground over a complete heating/cooling period of a year [1]. This operation system is preferred by the ecologist due to its environmental friendly for the sustainability of groundwater.

Heat transfer in energy piles system is surrounded by complex process. In the first circuit, the transfer depends on soil thermal and hydrology properties, which are specifically conducted by thermal conductivity, specific heat extraction, and water content of soil. In the second circuit, thermal transfer affects mechanical behaviour at concrete piles, predominantly related to the interaction between soil–concrete piles–and upper structure. Finally, coefficient of performance of heat pumps is the key to avoid the energy loss between the second and third circuit. Because of the fact that no design method is yet available to consider the complex interaction between thermal storage and the mechanical behaviour of energy piles [11], the present work offers some steps to implement energy piles' technology as explained at flowchart in Fig. 3.

3. Physical process in heat transfer

Soil is a porous medium formed by solid grains, water, and gases. Due to their compositions, heat transfer in soil consist of many mechanism, including: conduction through the soil grains, liquid, and gases; convection through liquid and vapour diffusion; latent heat transfer through evapouration–condensation cycles during the phase change of water; radiation in gas-filled pores; and freezing–thawing process that should be avoided in energy foundations system [8,12]. Heat conduction leads dominantly, heat convection in liquid diffusion occurs by presence of groundwater flow, vapour diffusion and latent heat transfer might only possible in unsaturated soil, and radiation contributes negligibly to heat transfer.

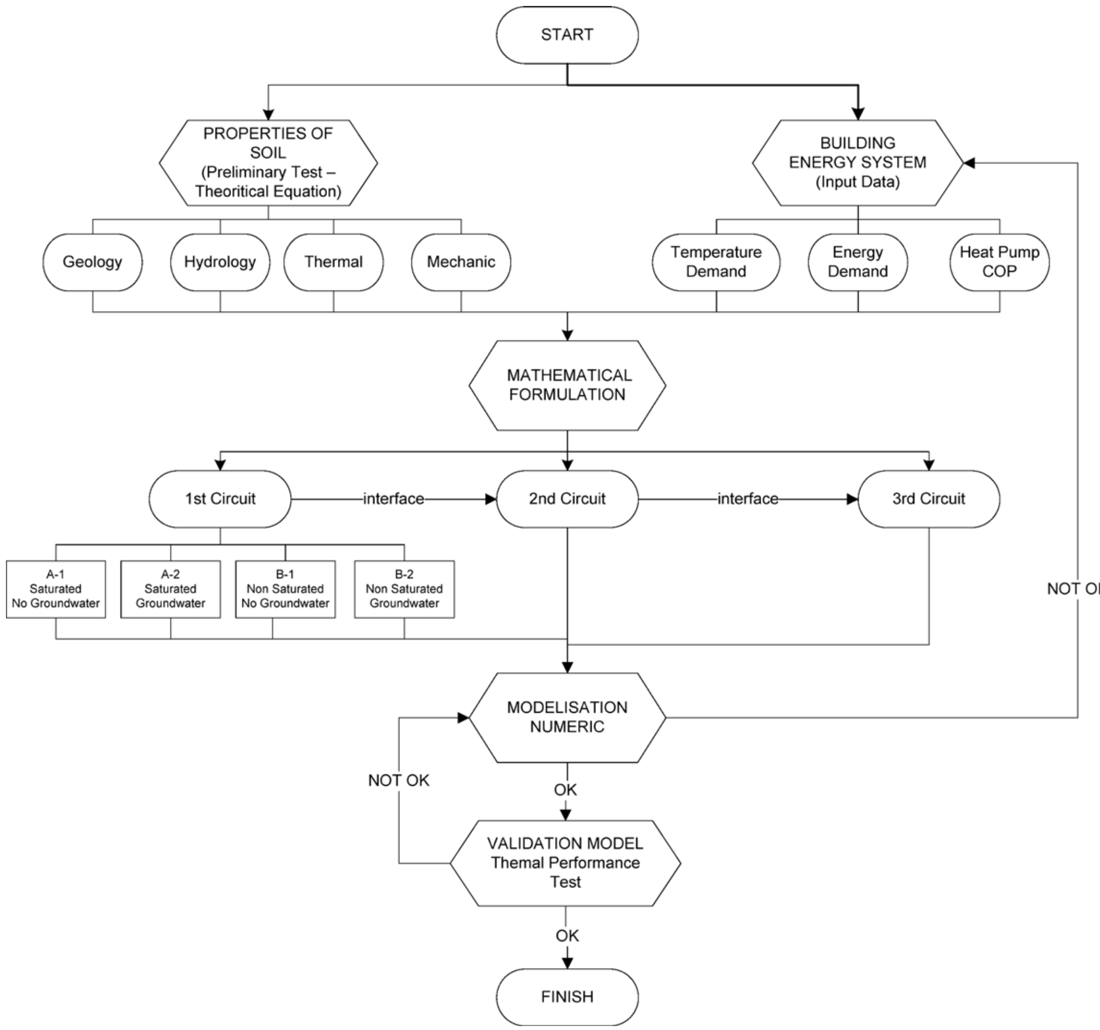


Fig. 3. Flow chart of design steps.

3.1. Ground temperature

Burger et al. [13] divides the soil into three zones of temperature: heterothermal, neutral, and homothermal zone. External temperature and radiation affect ground temperature in heterothermal zone. In this zone, temperature varies in time and depth as function $T(z,t)$: where $T(t)$ defines thermal cycle loads in annual external temperature and $T(z)$ indicates thermal waves' propagation in depth. This is the most critical zone depth that should be properly taken in account of energy piles design calculation. The function of temperature forms a sinusoidal wave, as following equation:

$$T(z,t) = T_{ave} + A_0 e^{-(z/d)} \left(\sin \left(\omega t - \frac{z}{d} \right) \right) \quad (1)$$

where T_{ave} is the average annual soil temperature; A_0 is maximum annual amplitude; z is the depth in which temperature is investigated; d is the damping depth of annual fluctuation; and ω is the annual radial frequency.

Fluctuation of temperature becomes constant since it arrives in neutral zone at depth 10 m until 50 m below the surface [13] and remains closely at average air temperature, where the value depends on altitude h:

$$\bar{T}_{air} = 11.3 - 0.52h \quad (2)$$

In homothermal zone, temperature is no longer influenced by external thermal flux and no longer varies by annual sinusoidal waves. This zone is where the deep geothermal or internal terrestrial flux takes place. Temperature increases regularly in depth with geothermal gradient 3 °C per 100 m [14].

3.2. Soil thermal properties

Heat flux propagation in soil is transmitted by heat capacity and thermal conductivity. Volumetric heat capacity C_v is a product of mass volume ρ with specific heat extraction c that indicates the ability of a substance to store heat energy. The greater its heat capacity, the more heat it can gain or lose per unit rise or fall in temperature. Whereas thermal conductivity λ is the quantity of heat transferred through a unit area of the conducting body in unit time under a unit temperature gradient [15]. This indicates the rate at which heat will be transferred between exchanger loops and the surrounding transfer medium for a given temperature gradient. Thermal conductivity of the surrounding transfer medium is the critical value that determines the number of heat exchanger pipes required to produce energy needs of building by pumping specific fluid temperature through the ground loops.

Thermal properties of soil, including heat capacity and thermal conductivity, cannot be separated with mineral composition of soil itself as mentioned in Eqs. (3) and (4) with index "s" denotes solid composition and "f" denotes fluid composition. Porosity factor n, water and air content will lead the quantity of heat produced. Moist or saturated soils have greater thermal capacity than dry soils, since

thermal conductivity for dry soil is about five times lower than that of a saturated soil [14].

$$C_v = (1-n)\rho_s c_s + n\rho_f c_f \tag{3}$$

$$\lambda = (1-n)\lambda_s + n\lambda_f \tag{4}$$

3.3. Groundwater flow

As water and air content take important place in producing thermal capacity of soil, the presence of groundwater flow is one of key factor in heat transfer mechanism. In fully saturated soil with no presence of pore gas, groundwater composes only of liquid flow, so that heat convection occurs in liquid diffusion. In unsaturated soil where the pore gas presences inevitable, groundwater flow has both of liquid and vapour flow, so that heat convection counts both liquid and vapour diffusion. It is also possible to have a water phase change into fully vapour that correlates with vapour latent transfer. A widely used theory for coupled heat and moisture flow through soils was developed by Philip and de Vries [16] for both liquid and vapour phase flows.

Groundwater flow in soil varies under water content θ and temperature T gradients. Water content variation is led by isothermal diffusivity D_θ while temperature variation is controlled by thermal diffusivity D_T. In general, water content gradient is less than those of temperature, therefore the flux due to water content gradient is more important than those due to temperature gradient, even with the maximum temperature gradient [16]. Hadley and Eisenstadt [17] have observed that moisture transfer under temperature gradient is negligibly small both in very dry (unsaturated) and in very wet (saturated) media [16,17].

In liquid phase, the velocity of groundwater is given by Eqs. (5)–(7), referring to Darcy's equation where k is hydraulic conductivity and i is unit vector in vertical direction. Here, isothermal liquid diffusivity $D_{\theta,l}$ and thermal liquid diffusivity $D_{T,l}$ depend on capillary suction head ψ and surface capillary tension σ.

$$\vec{v}_l = -D_{\theta,l} grad \;\; \theta - D_{T,l} grad \;\; T - ki \tag{5}$$

$$D_{\theta,l} = k\frac{\partial\psi}{\partial\theta} \tag{6}$$

$$D_{T,l} = k\frac{\psi}{\theta}\frac{\partial\sigma}{\partial T} \tag{7}$$

Movement in vapour phase is a process of the diffusion of water vapour in the air-filled pores which can be approximated by modifying the Fick's law of diffusion:

$$\vec{v}_v = -D_{T,v} grad \;\; T - D_{\theta,v} grad \;\; \theta \tag{8}$$

where $D_{T,v}$ is the thermal vapour diffusivity and $D_{\theta,v}$ is the isothermal vapour diffusivity.

Groundwater flow is then a sum of flow in liquid and vapour phase. The two liquid diffusivities tend to be the most important ones at high moisture contents, whilst the two vapour diffusivities are dominant at low moisture contents [16]. Refers to precedent hypotheses, groundwater flow in saturated soil is given in Eq. (9) while in unsaturated soil is mentioned in Eq. (10).

$$\vec{v}_{sat} = -k\frac{\partial\psi}{\partial\theta} grad \;\; \theta = -k \;\; grad \;\; \psi \tag{9}$$

$$\vec{v}_{unsat} = -D_{\theta,v} grad \;\; \theta \tag{10}$$

Site installation of Finkernweg at Switzerland has been conducted by Fromentin et al. [5], concerning 75 energy piles with 11 m active length to produce 90 kW and 7000 m^3 heat energy. Thermal measurement is investigated during February until May 1995. It is shown that groundwater flow does not have significant influence in short term operation. However, groundwater flow may reproduce heat concentration energy around the piles with velocity up to 10 cm/day in long-term period [5] so that it plays an important role for pile's dimensioning. Also, if a flow of water is present and sufficiently large, a natural regeneration of the soil is achieved [14]. As a result, the amount of heat extracted during winter (for heating) no longer depends on the amount injected in the summer (for the cooling). Hence, groundwater flow is of advantage to single mode energy extraction system but further study is required to ensure sustainability of ground water.

3.4. Heat flux

The rate of energy transfer in soil through solid, liquid, or gas pores is called as heat flux. It is important to define the heat flux in order to quantify the energy produced.

For heat conduction mechanism, heat flux is based on Fourier law:

$$\vec{q}_{cond} = -\lambda \;\; grad \;\; T \tag{11}$$

while in liquid convection mechanism is determined by:

$$\vec{q}_{conv} = \rho_f c_f \vec{v}_l (T - T_0) \tag{12}$$

It should be noted that groundwater flow in heat convection flux is the groundwater flow in liquid diffusion. In reverse when we consider latent heat flux, groundwater flow which contributes in energy transfer is groundwater flow in vapour diffusion, as mentioned as:

$$\vec{q}_{latent} = L_v \vec{v}_v \tag{13}$$

3.5. Energy conservation

Finally, heat transfer in soil should satisfy the energy conservation of thermodynamics law, which is:

$$C_v\frac{\partial T}{\partial t} + \nabla\vec{q} = 0 \tag{14}$$

Table 1 summarises heat transfer mechanism for each type of soils and their energy conservations are given in Eqs. (15)–(18).

For saturated soil with no groundwater flow:

$$C_v\frac{\partial T}{\partial t} = div(\lambda \;\; grad \;\; T), \tag{15}$$

for saturated soil with groundwater flow:

$$C_v\frac{\partial T}{\partial t} - \rho_f c_f k \;\; grad \;\; \psi \;\; grad \;\; T = div(\lambda \;\; grad \;\; T), \tag{16}$$

for unsaturated soil without groundwater flow:

$$C_v\frac{\partial T}{\partial t} = div(\lambda \;\; grad \;\; T) - L_v \;\; div(D_{\theta,vap} \;\; grad \;\; \theta), \tag{17}$$

and for unsaturated soil with groundwater flow:

$$C_v\frac{\partial T}{\partial t} - \rho_f c_f k \;\; grad \;\; \psi \;\; grad \;\; T = div(\lambda \;\; grad \;\; T) - L_v \;\; div(D_{\theta,vap} \;\; grad \;\; \theta) \tag{18}$$

4. Thermal transfer balance

Energy piles are dual-purpose as structural foundation and heat exchanger. Thermal capacity of their heat exchanger elements will take a role for structural dimensioning of their foundation elements. Their functions to satisfy thermal and mechanical (structural) capacity should be carefully designed by mechanical and geotechnical engineers. For $\dot{Q}_3$ is the energy required of building at

Table 1
Division of heat transfer process in soils.

Heat transfer	Saturated		Unsaturated	
	No ground-water flow	With ground-water flow	No ground-water flow	With ground-water flow
In solid conduction	v	v	v	v
In liquid convection	x	v	x	v
In vapour latent	x	x	v	v

Table 2
Properties of model.

Thermo-elastic properties		Unit	Soil	Concrete
Density	ρ	Pa	1950	2500
Bulk modulus	E	MPa	10	20,000
Shear modulus	G	MPa	3.75	7500
Thermal conductivity	λ	W/m^2	1.5	1.8
Specific heat extraction	c	J/kg °C	800	880
Coefficient of thermal expansion	α	J/°C	5×10^{-6}	1×10^{-5}

Thermo-elastoplastic properties		Unit	Interface
Normal stiffness	k_n	MN/m	22
Shear stiffness	k_s	MN/m	8.33
Cohesion	c	kPa	1
Friction angle	ϕ	°	30

third circuit and $\dot{Q}_2$ is input energy at heat pump at second circuit, the energy conservation which occurs in the heat pump is:

$$\dot{Q}_3 = \dot{Q}_2 + P_{HP} \tag{19}$$

$$\dot{Q}_3 \left(1 - \frac{1}{COP}\right) = \dot{Q}_2 \tag{20}$$

Input energy at heat pump $\dot{Q}_2$ is equal to resources heat energy from soil through concrete piles $\dot{Q}_1$. Hence, to design the number n of concrete piles required, Eqs. (21) and (22) are given as below, where l is the length of material.

$$\dot{Q}_2 = \dot{Q}_1 \tag{21}$$

$$\int (n\vec{q}C_v dl)_{concrete} = \int (\vec{q}C_v dl)_{soil} \tag{22}$$

To minimise energy loss between each circuit, high-raised energy can be produced by the help of heat pumps performance. Study of thermal performance of energy piles applied at Zurich Airport showed that annual heat pump performance coefficient is 3.9. The overall system efficiency, defined by the ratio of the thermal energy delivered by the system (heating and cooling) over the total electric energy required to run it, is established to 5.1 [4]. With a high efficiency system, energy piles will maintain in long-term operation with less energy loss.

5. Mechanical equilibrium

In general, the mechanical response of a system must satisfy equilibrium, compatibility, material constitutive behavior and boundaries conditions [18]. Among these conditions, thermal effect is involved in mechanical response of energy piles. Indeed, the change of temperature both in concrete and soil will produce supplementary thermal deformation that will modify the strain state of materials. The quantity of thermal deformation εth is a product of thermal expansion coefficient α with gradient temperature occurred as mentioned in Eq. (23). Elastic deformation ε^e will change in function of thermal deformation obtained and total deformation ε caused by static weights of system structure, given in Eq. (24).

$$\varepsilon\text{th} = \alpha \Delta T \tag{23}$$

$$\varepsilon^e = \varepsilon - \varepsilon\text{th} \tag{24}$$

Since lateral movements of concrete pile are restrained by soils, thermal deformation will mainly occurs in vertical axis of pile. The vertical displacements are not uniform in depth and strongly relates to lateral friction mobilised in the shaft of pile, in contact with soil [19]. The supplementary thermal deformation brings out increasing of mobilised shaft friction at interface soil-concrete piles also uplift displacement and additional thermal compressive stress at interface concrete piles–upper structure [20]. The relation between axial force Q, mobilised shaft friction q_s, and deformation at a given depth z is expressed on following equation [21]:

$$Q(z) = \varepsilon^e(z) A E_{pile} \tag{25}$$

$$q_s(z) = \frac{Q(z)}{A_s(z)} = \frac{AE_{pile}}{A_s(z)} \frac{\Delta\varepsilon^e(z)}{dz} \tag{26}$$

where E_{pile} is young modulus of concrete pile, A is area of pile's section, A_s is shaft area at certain depth.

A four storey building built with 97 piles was carried out to an in situ test of a heat exchanger pile at the Swiss Federal Institute of Technology in Lausanne (EPFL). Data from tests indicate that a temperature increment of 1 °C results in an additional temperature-induced vertical force on the order of 100 kN [22]. As a consequence, the total axial load in the pile is twice as large as the one due to purely mechanical loading, with a large solicitation of the toe because the pile toe sits on very stiff sandstone that restrain the pile.

Another in situ test of energy piles was conducted in Lambeth College, United Kingdom with a total 143 piles. The different with those from Lausanne test is in this test, the piles are floating in the ground so that both ends of pile are free to move. When a cooling cycle is applied to the pile, the pile contracts and leads to induce tensile force. Along the upper part of the shaft, mobilised lateral friction on the interface soil-pile will increase in the same sense as that mobilised by compression loading applied at the pile head, while in the lower part of the pile will be in the opposite sense so reduce the mobilised friction [23]. The reverse responses are appeared when a heating cycle is applied, which suggest the pile behaves in purely thermo-elastic.

If the energy piles work on seasonal mode operation system, they are subjected by alternate thermal loads. The alternate

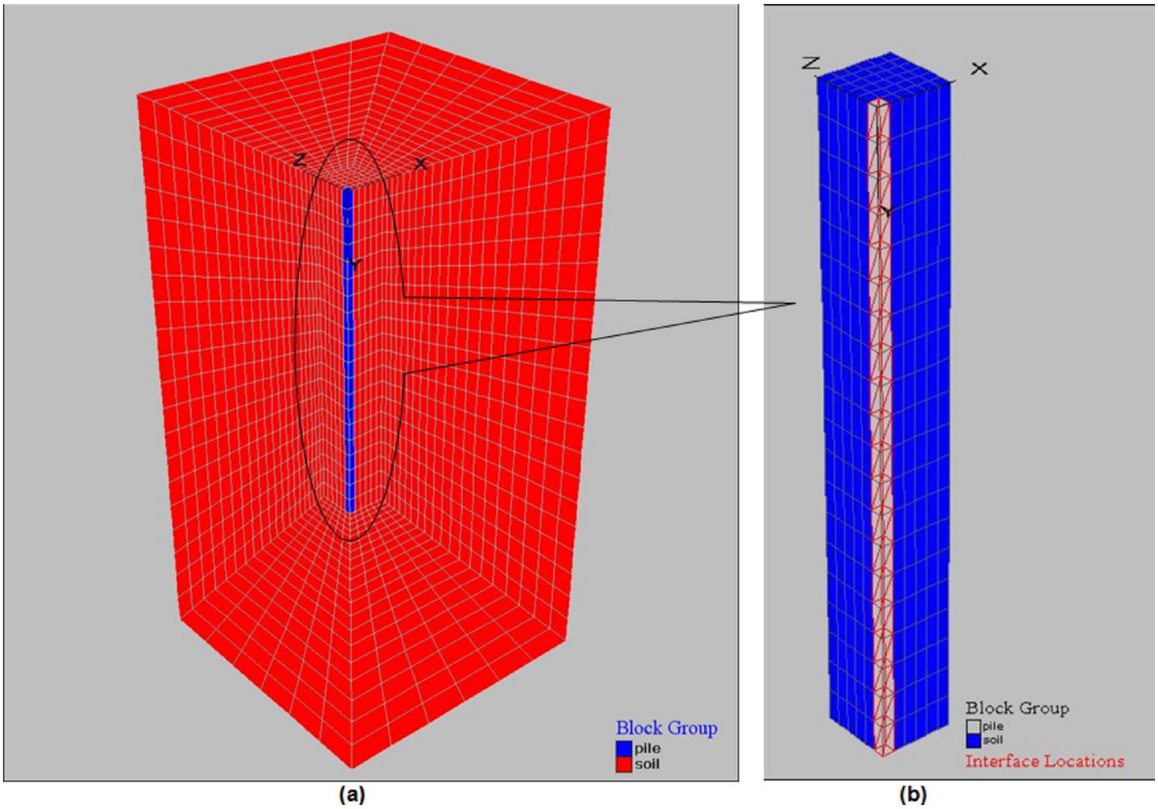


Fig. 4. 3D mesh discretisation of model: (a) one-fourth of model and (b) interfaces location at Model 2.

contraction/expansion piles create cyclic behaviour at interface soil–concrete piles–and upper structure. As explained in Section 2, from an energy balance point of view, seasonal mode operation system is the most favourable one referring to energy balance point of view. But if we look from the view of mechanical durability, cyclic behaviour at interface will decrease strength resistance of structure.

6. Case study: temperature-induced mechanical behaviour of an energy pile under static thermal loading

6.1. Numerical model

Numerical method such as finite difference method provides an efficient tool for solving complicated partial differential equations such as those that govern the thermo-hydro-mechanical problem of energy pile, because of its ability to integrate complexities arising from: geometry, thermo-hydro-mechanic loading, interaction between different rigidity bodies, etc. The case under study concerns with the analysis of an energy pile under static thermal loading. A single pile with a square section of $B = 60$ cm and length $L = 15$ m is founded into a homogeneous soil mass. Both of pile and soil are assumed to behave into linear thermo-elastic domain. Properties of materials are shown in Table 2, where thermal properties are chosen in reference to Hillel [15].

Analyses are carried out using finite difference code FLAC^{3D} [24]. Fig. 4a shows the numerical mesh used into the numerical modelling. Owing to the symmetry of the problem (symmetry of load and geometry), only one-fourth of the complete domain is modelled. The mesh was fixed after a parametric analysis concerning the lateral extension of the soil domain. The soil is refined around the pile, in order to increase precision in the areas of high strain gradient. According to Karthigeyan et al. [25] and Mroueh and Shahrour [7], the soil mass dimension depends on the pile section and length. Lateral extension of the domain is equal to 15 m (25B). The height of soil mass is equal to 30 m (2 L). As mentioned in Section 1, the response of piles to vertical loads strongly depends on the characteristics at the soil–pile interface [6,7]. This study

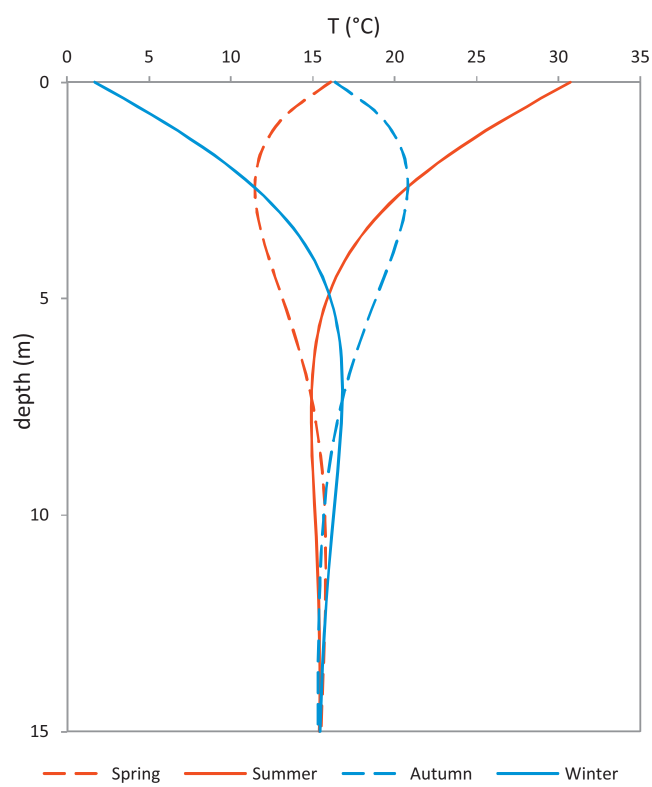
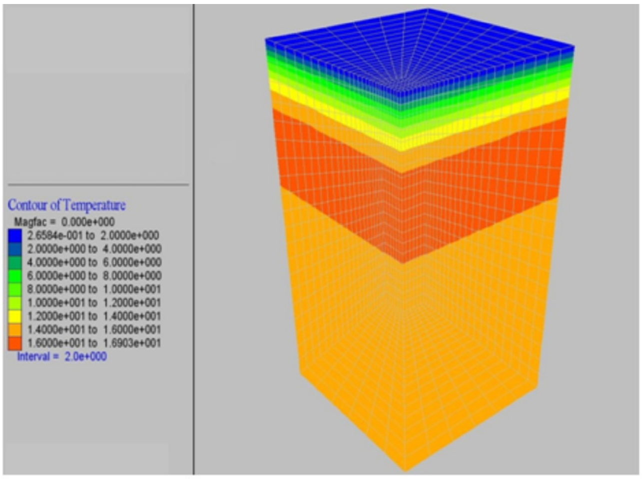
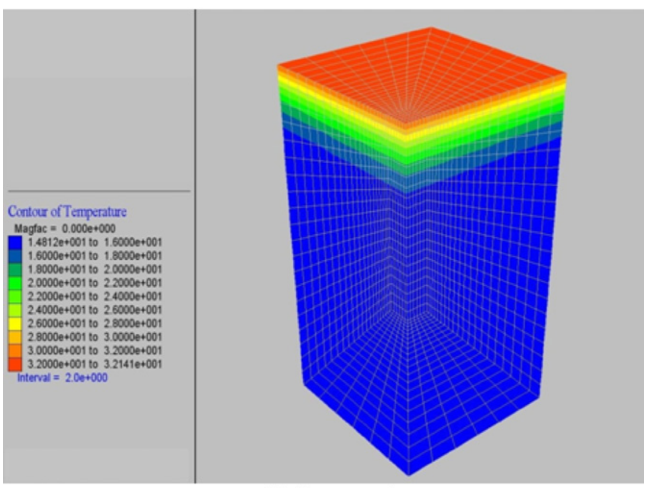


Fig. 5. Fluctuation of initial ground temperature.



(a) Winter mode



(b) Summer mode

Fig. 6. Initial condition of ground temperature.

proposes comparison of two conditions of soil–pile contact in order to understand their different behaviour. Model 1 considers a perfect contact between soil and energy pile that means there is no relative movement between the nodes of pile and soil. Model 2 introduces frictional model for the soil–pile interface, governed by an elastic perfectly plastic behaviour. These interfaces elements are able to localise relative movements and frictions mobilised between two different solids (Fig. 4b). Elasticity part is described by the following relation:

$$\begin{pmatrix} \tau \\ \sigma_n \end{pmatrix} = \begin{bmatrix} k_s & 0 \\ 0 & k_n \end{bmatrix} \begin{pmatrix} \varepsilon_t \\ \varepsilon_n \end{pmatrix} \tag{27}$$

where τ and σ_n denote the shear and normal stress and ε_t and ε_n indicate the shear and normal strain at the interface, respectively. The interface shear stiffness k_s and the normal stiffness k_n are chosen in accordance with interfaces' theory and background of the code FLAC^{3D} [24]. Plasticity part is defined by a yield surface based on the Coulomb failure criterion:

$$|\tau| = \sigma_n \tan \varphi_i + c_i \tag{28}$$

where φ_i and c_i are the friction angle of interface and cohesion factor at interface. The interfaces properties are shown in Table 2.

At first, soil system is initialised by sinusoidal surface temperature with average ground temperature 14 °C. The soil has internal terrestrial heat volume r as 0.001 W/m^3 and terrestrial surface flux

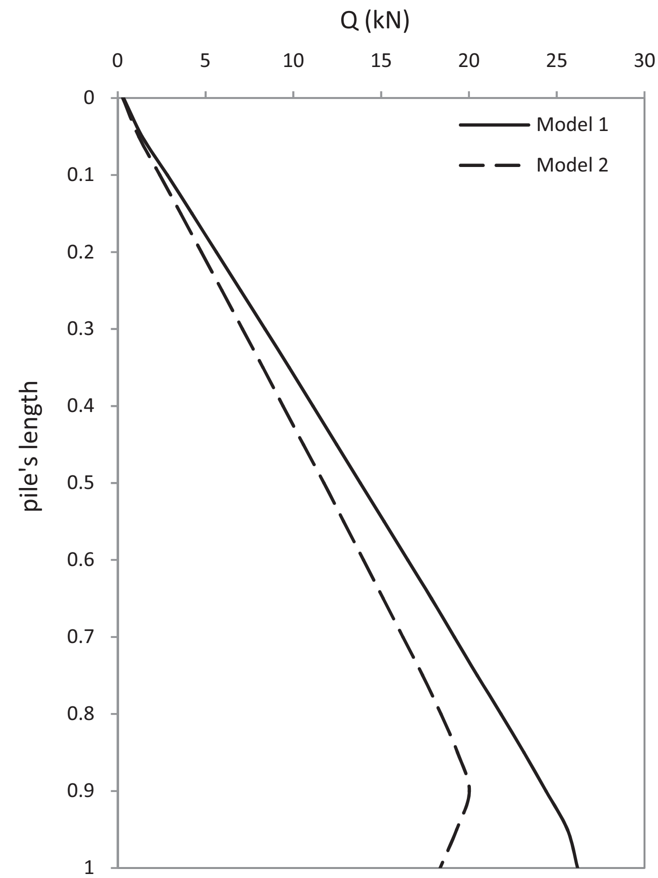


Fig. 7. Normal forces due to gravity load.

$\vec{q}$ at depth 30 m as 0.0544 W/m^2. Due to symmetrical condition, flux null is imposed in symmetrical axes. The presence of groundwater flow is neglected in assuming that soil is fully saturated so that heat diffusion works in purely conduction. This sinusoidal surface temperature produces fluctuation of ground temperature in depth and in time that becomes constant near to average ground temperature at the depth >10 m (Fig. 5). This is justified by theoretical hypothesis in Section 3.1.

According to that fluctuation, seasonal inlet fluid temperature is applied into the pile and assumed to be uniform along the pile's axis. The model is conducted in two separated operation time: (a) winter mode operation with inlet temperature is set on 5 °C (cooling cycle – Model W) and (b) summer mode operation with inlet temperature 25 °C (heating cycle – Model S). Initial temperature of soil before the injection of inlet fluid at each season is shown in Fig. 6.

The pile is only subjected by gravity load and then by temperature applied during six months loading for each operation mode. No service load coming from upper structure is considered to properly understand the effect of thermal load in pile's mechanical behaviour. Fig. 7 shows the initial normal forces due to gravity load in two different conditions of contact. For the clarity, positive sign signifies compression on forces and settlement on displacements. Model 2 with interfaces imposed in the zone of contact gives reduction of normal forces in pile because interface zones take a role to transfer the forces more uniformly to the system by reducing discontinuity of residual forces.

Comparison of thermal diffusion by the function of contact's condition shows a remarkable influence (Figs. 8 and 9). Within the presence of interface elements, there is high concentration of thermal field at surface contact between pile and soil. This leads to a statement that interface behaviour depends also on temperature as

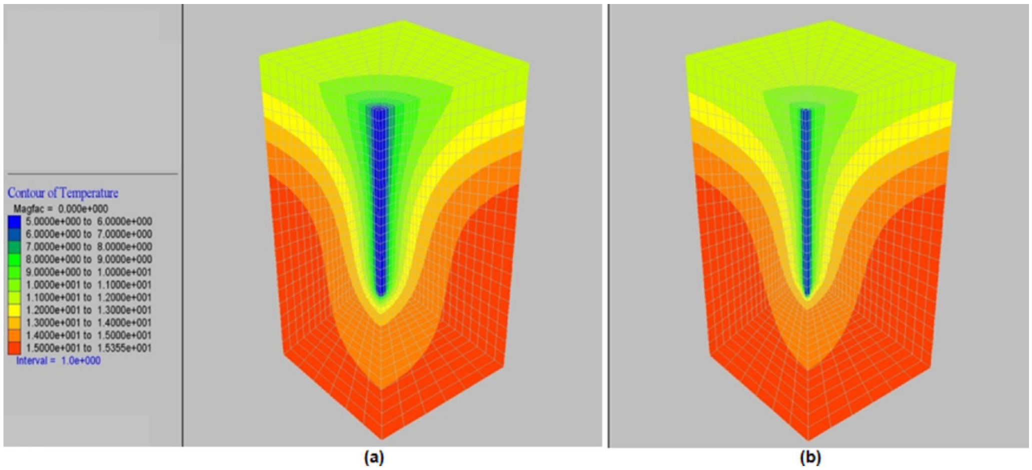


Fig. 8. Field of temperature after cooling cycle: (a) Model 1 perfect contact and (b) Model 2 with interfaces.

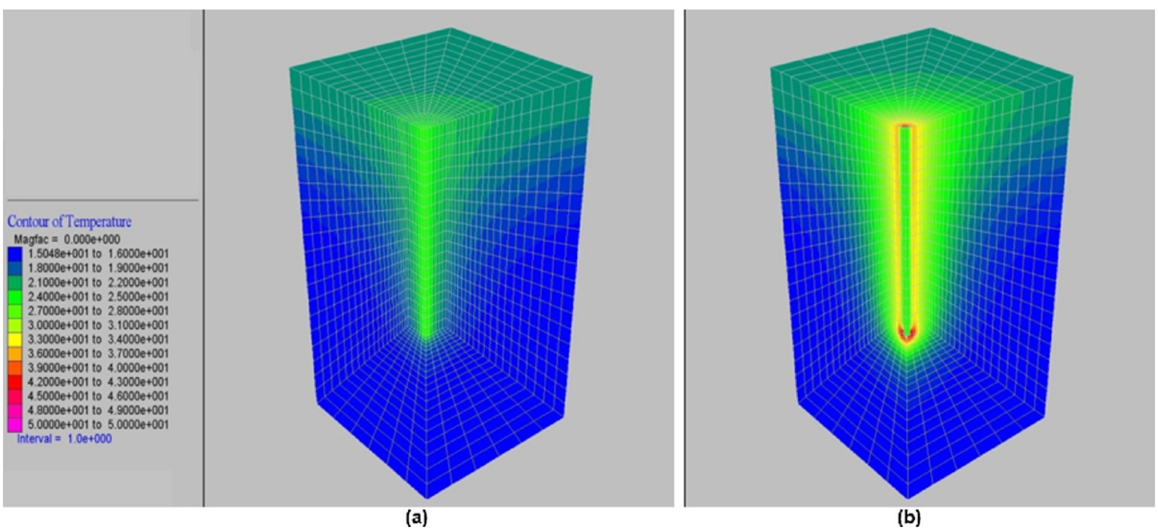


Fig. 9. Field of temperature after heating cycle: (a) Model 1 perfect contact and (b) Model 2 with interfaces.

a function parameter, that interface nodes take a role on temperature transfer. It is suggested to conduct further study to look about interface behaviour law with the coupling of temperature function.

Concerning to the mechanical behaviour due to thermal loading, thermal displacement of the surface and along the pile are shown in Figs. 10 and 11. Winter mode operation produces a settlement at surface plus shortening of pile while summer mode operation leads to an uplift surface with expansion of pile. Contraction in winter mode induces tensile forces at the pile while dilatation in summer mode adds compressive forces at the pile. Model 2 with interfaces imposed gives clearly different mechanical responses and also reduces the value of temperature-induced normal forces produced (Fig. 12).

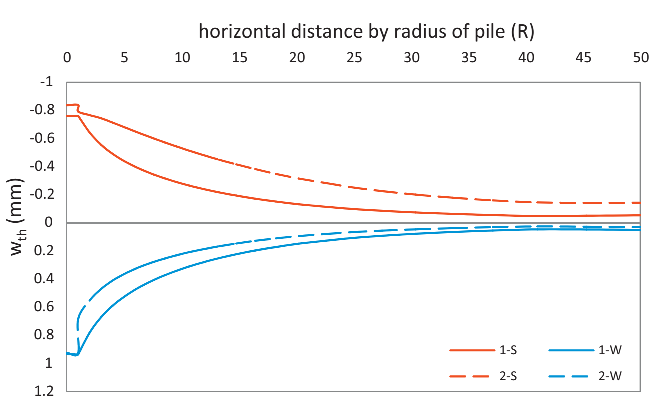


Fig. 10. Thermal surface displacements.

Fig. 13 shows frictions mobilised along interface soil–pile at Model 2. Due to its contraction in winter mode, frictions mobilised along the upper part of pile increase whereas along the lower part of pile decrease. Inversely in summer mode, a reduction of frictions mobilised is appeared at upper part of pile while the lower part of pile has additional frictions mobilised. At middle part of pile, the friction mobilised tends to be constant as what it's called null point. This behaviour is only occurred when both ends of pile are freely restrained. These results are in good agreement with in situ tests conducted at Lambeth College, UK [23].

6.2. Perspectives

According to this preliminary numerical model, static thermal load in only cooling/heating operation give slight influence on mechanical behaviour of pile. Alternate contraction and dilatation during seasonal operation time is predicted to be a dominant factor

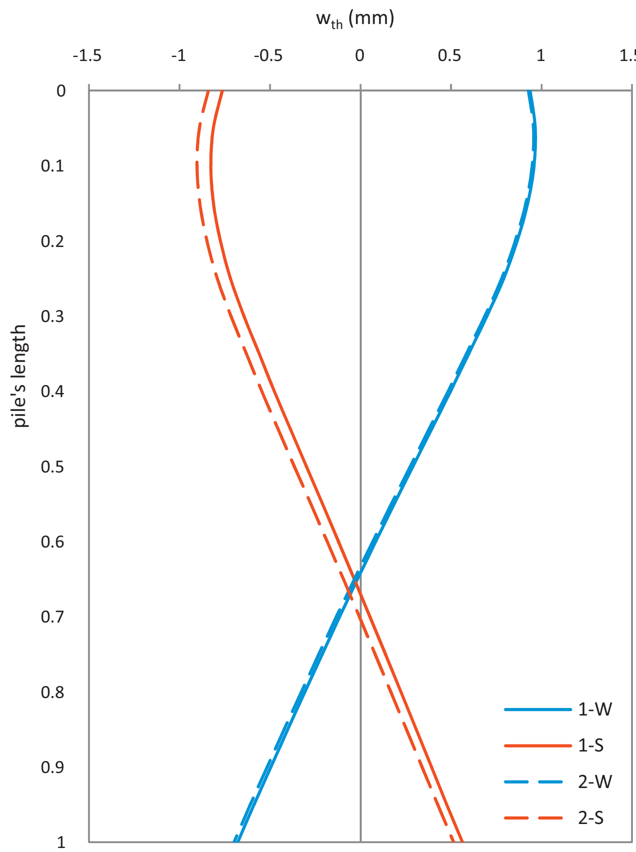


Fig. 11. Thermal vertical displacements of pile.

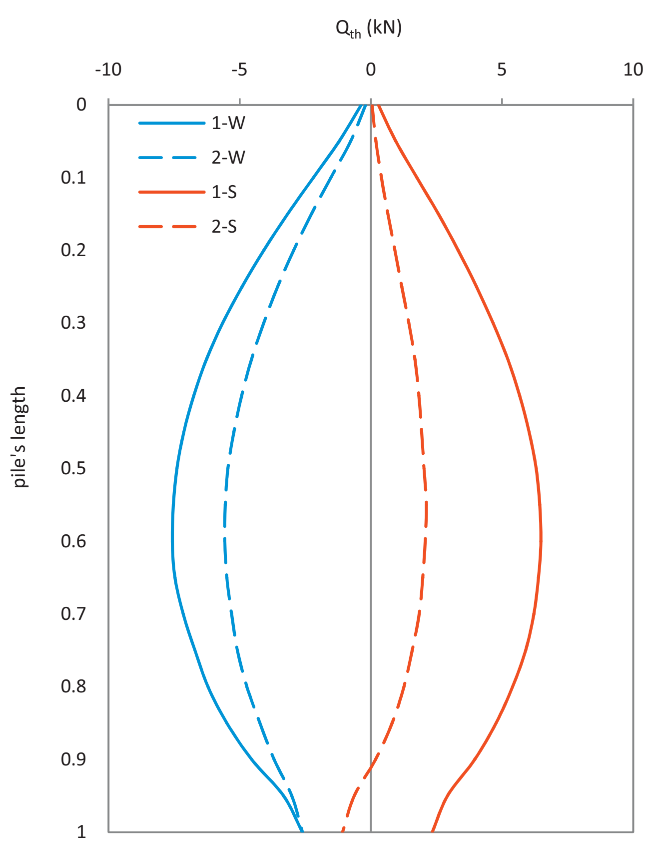


Fig. 12. Temperature-induced normal forces in the pile.

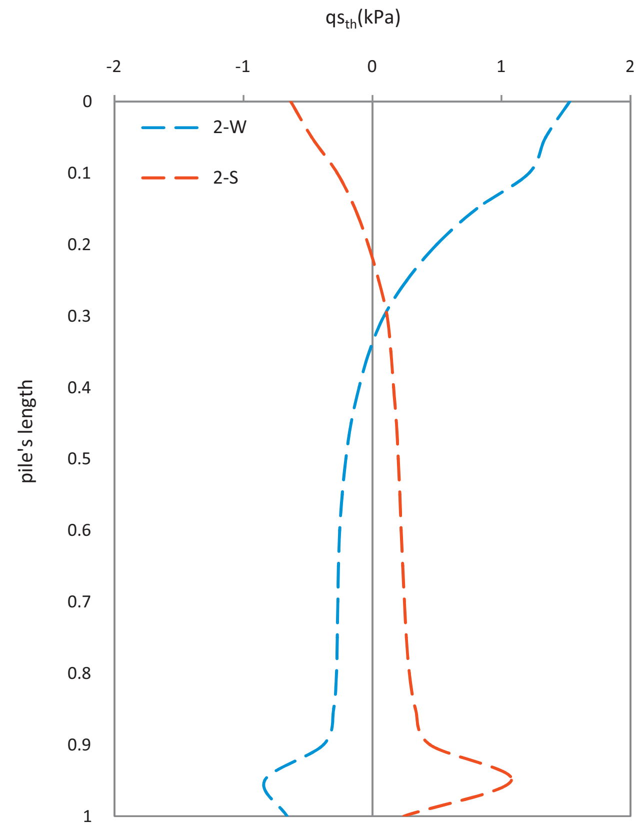


Fig. 13. Temperature-induced frictions mobilised at interface soil–pile.

that provokes a strong degradation of structure's resistance, especially at interface soil–structure.

Our perspective is to determine the interface behaviour between soil–structure due to thermal cyclic solicitation. To achieve this goal, it is better to consider an appropriate law that can define cyclic behaviour of interface soil–structure in taking into account plasticity condition. It should consider also the effect of delta temperature occurred at interface behaviour. On-going works have developed a constitutive law for interface soil–structure under mechanical cyclic loading, based on previous work of Shahrour and Rezaie [26]. This law takes into account kinematic hardening rules that allow to describe kinematic surface in each cycle loading. The further research aims to adopt this constitutive law into thermal regime, coupled with mechanical service loads.

7. Conclusions

Energy piles are bi-function foundations which support the loads of structure and provide thermal energy to the building as heat exchangers. They're using shallow geothermal energy as heat source, successfully considered as an innovative environmentally friendly building's technology. Energy piles can work in two system operations: (a) only cooling/heating operation system for glacial/tropical countries and (b) seasonal cooling-heating operation system for four-season countries. The latter one is the most favourable for its automatic energy balance throughout the year.

This paper covered a sum of literature study to identify the remaining problems in energy piles' application. Quantity of heat energy produced depends on type of soil, saturation degree, presence of groundwater flow, and of course heat pump's specification. On the other hand, delta temperature occurred delivers additional thermal deformation and thermal stress that change the behaviour of material, especially friction mobilised at interface soil–concrete

piles also head uplift displacement and axial forces at interface concrete piles-upper structure.

A preliminary numerical simulation is conducted with finite difference method under static thermal load for only cooling and only heating operation. The study considered two different conditions of contact between soil and an energy pile: perfectly contact and sliding contact with frictional interface elements. In this case, the pile is freely restrained both at its ends. The results show that by the presence of interfaces at zone of contact between soil and pile, the stresses and displacements obtained are lower than those with perfect contact. Cooling cycle in winter mode results in pile's contraction so that produces surface's settlement and temperature-induced tensile forces at pile. If interfaces are imposed at surface of contact, cooling cycle increases frictions mobilised at the upper part of pile while reduces at the lower part of pile. Reverses responses are obtained at heating cycle in summer mode. A higher gradient temperature applied will possibly create negative friction at interface soil–structure. There is a node at the middle part of pile that is not influenced by temperature-induced friction mobilised, which is called null point. This behaviour of energy pile under thermal load is none of difference with the results of in situ tests at Lausanne and Lambeth College.

Numerical simulation under thermal static loads for only cooling/heating operation pointed out that there is slight influence in mechanical behaviour of pile. The problem in this kind of operation system lies in quantity of energy balance. Mechanical behaviour will be affected in seasonal operation time since the piles are subjected by cyclic thermal loadings during annual operation. It is suggested to concentrate on behaviour of interface due to cyclic solicitation in thermal regime with appropriate cyclic behaviour law of interface soil–structure considering coupling with temperature function for further studies.

References

[1] Adam D, Markiewicz R. Energy from earth-coupled structures: foundations, tunnels and sewers. Géotechnique 2009;59(3):229–36.

[2] Quick H, Meissner S, Michael J. Innovative foundation systems for high-rise buildings. In: The 1st Intelligent Building Middle East Conference. 2005.

[3] Kefford N, In: GSHPA Research Seminar. Case study: long term monitoring of energy piles at Keble College, Oxford. ARUP; 2010.

[4] Pahud D, Hubbuch M. Measured thermal performances of the energy pile system of the dock midfield at Zürich Airport. In: European Geothermal Congress. 2007.

[5] Fromentin A, Pahud D, Laloui L, Moreni M. Pieux échangeurs: conception et règles de pré-dimensionnement. Revue française de génie civil 1999;3(6):387–421.

[6] De Gennaro V, Frank R. Modélisation de l'interaction sol-pieu par la méthode des éléments finis. Bulletin des Laboratoires des Ponts et Chaussées 2005:107–33.

[7] Mroueh H, Shahrour I. Numerical analysis of the response of battered piles to inclined pullout loads. International Journal for Numerical and Analytical Methods in Geomechanics 2009;33(10):1277–88.

[8] Brandl H. Energy foundations and other thermo-active ground structures. Géotechnique 2006;56(2):81–122.

[9] Hamada Y, Saitoh H, Nakamura M, Kubota H, Ochifuji K. Field performance of an energy pile system for space heating. Energy and Buildings 2007;39(5):517–24.

[10] Lund J, Sanner B, Rybach L, Curtis R, Hellström G. Geothermal (ground-source) heat pumps—a world overview. GHC Bulletin 2004:25.

[11] Knellwolf C, Peron H, Laloui L. Geotechnical analysis of heat exchanger piles. Journal of Geotechnical and Geoenvironmental Engineering 2011;137(10):890–902.

[12] Deru MP, Kirkpatrick AT. Ground-coupled Heat and Moisture Transfer from Buildings Part 1: Analysis and Modeling. In: American Solar Energy Society (ASES) National Solar Energy Conferences Forum. 2001.

[13] Burger A, Recordon E, Bovet D, Cotton L, Saugy B. Thermique des nappes souterraines. Laussane: Presses Polytchniques Romandes; 1985.

[14] Riederer P, Evars G, Gourmez D, Jaudin F, Monnot P, Partenay V, et al. Conception de Fondations Geothermiques - Rapport Final; 2007, Centre Scientifique et Technique du Bâtiment: Sophia-Antipolis.

[15] Hillel D. Soil temperature and heat flow. Introduction to environmental soil physics. Elsevier Science; 2004. p. 215–34.

[16] Philip JR, de Vries DA. Moistrure movement in porous materials under temperature gradients. Transactions—American Geophysical Union 1957;38:222–32.

[17] Hadley WA, Eisenstadt R. Thermally actuated moisture migration in granular media. Transactions–American Geophysical Union 1955;36:615–23.

[18] Potts D, Axelsson K, Grande L, Schweiger H, Long M. Geotechnical analysis. In: Guidelines for the use of Advanced Numerical Analysis. Thomas Telford Publishing; 2002, p.15–29.

[19] Laloui L, Moreni M, Vulliet L. Comportement d'un pieu bi-fonction: fondation et échangeur de chaleur. Canadian Geotechnical Journal 2003;40(2):388–402.

[20] Laloui L, Moreni M, Fromentin A, Pahud D, Steinmann G. Heat exchanger pile: effect of the thermal solicitations on its mechanical properties. Bulletin d'Hydrogéologie 1999;17.

[21] Vulliet L, Meyer A. The Vigner tunnel: determining contact laws from static load tests on piles. In: The 12th European Conference on Soil Mechanics and Foundation Engineering. Rotterdam: A.A. Balkema; 1999.

[22] Laloui L, Nuth M, Vulliet L. Experimental and numerical investigations of the behaviour of a heat exchanger pile. International Journal for Numerical and Analytical Methods in Geomechanics 2006;30(8):763–81.

[23] Bourne-Webb PJ, Amatya B, Soga K, Amis T, Davidson C, Payne P. Energy pile test at Lambeth College, London: geotechnical and thermodynamic aspects of pile response to heat cycles. Géotechnique 2009;59(3):237–48.

[24] FLAC3D Version 3.0 User's Guide. Minnesota, USA: Itasca Consulting Group, Inc.; 2005.

[25] Karthigeyan S, Ramakrishna VVGST, Rajagopal K. Influence of vertical load on the lateral response of piles in sand. Computers and Geotechnics 2006;33(2):121–31.

[26] Shahrour I, Rezaie F. An elastoplastic constitutive relation for the soil–structure interface under cyclic loading. Computers and Geotechnics 1997;21(1):21–39.